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VEGETATION CHANGES AND PARTITIONING OF SELENIUM IN 4-YEAR-OLD CONSTRUCTED WETLANDS TREATING AGRICULTURAL DRAINAGE

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*The knowledge of selenium (Se) partitioning in treatment wetlands and wetland vegetation management are essential for long-term effective operation of constructed wetlands treating Se-laden agricultural tile-drainage in central California. In this field study, samples from different compartments of treatment wetlands were collected and the vegetation change in each wetland cell was examined four years after the wetland's inception. The results showed that saltgrass (*Distichlis spicata*) and rabbitfoot grass (*Polypogon monspeliensis*) were less competitive than cattail (*Typha latifolia*) and saltmarsh bulrush (*Scirpus robustus*). Over 90% of the wetland cell originally vegetated with saltgrass or rabbitfoot grass was occupied by invasive plants—i.e., when invasive species were not controlled in the wetlands. More Se was likely found in sediments from vegetated regions, compared to the unvegetated areas of the wetland cell. Particularly, rhizosphere sediments accumulated about 4-fold more Se than non-rhizosphere sediments. Among the total Se retained in the wetland, 90% of the total Se was partitioned in the top 10-cm layer of sediment. The Se accumulation in plant materials accounted for about 2% of the total Se mass retained in each wetland cell. This field study demonstrated that wetland plants play significant roles in the treatment of Se-laden agricultural drainage.*

KEYWORDS selenium, accumulation, vegetation, invasive species, wetland

INTRODUCTION

The management of large volumes of selenium (Se)-contaminated agricultural tile-drainage water has become one of the major environmental issues confronting California agriculture in the San Joaquin Valley, since Se was determined to be responsible for the death of migratory birds at the Kesterson Wildlife Refuge in early 1980s (Skorupa and Ohlendorf, 1991). Currently, the Se-laden drainage water is primarily disposed of in evaporation ponds/basins. However, previous studies indicated that such disposal could

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result in elevated concentrations of Se in the evaporation ponds, which may approach current water quality criteria for hazardous waste (Ong *et al.*, 1997). To reduce such potentially toxic loading of Se into evaporation ponds, a hypothesis was proposed in 1995 that flow-through constructed wetlands would effectively remove Se from selenate-laden agricultural drainage water before its discharge into evaporation ponds. This initiative came from an earlier study carried out at the Chevron Water Enhancement Wetland in Richmond, California; in that study, the flow-through constructed wetland removed 89% of the Se mass from selenite-contaminated oil refinery effluent (Hansen *et al.*, 1998). The success of the Chevron wetland in removal of selenite from effluent discharge led to the evaluation of a pilot flow-through constructed wetland project developed in the San Joaquin Valley.

Monthly monitoring results from May 1997 to December 1999 in the Corcoran wetlands showed that flow-through constructed wetlands removed substantial amounts (~69%) of Se mass from agricultural tile-drainage water (Lin and Terry, 2003). Of which vegetated wetland cells tended to remove more Se than the unvegetated/control wetland cell (Terry, 1998; Tanji, 1999; Gao *et al.*, 2003). Wetland vegetation not only forms much of the visible structure of wetland treatment systems, but also provides suitable growth media for microbes that facilitate most pollutant transformations (such as the reduction of selenate or oxidation of manganese) that occur in wetlands (Zhang and Frankenberger, 2007; Lesley *et al.*, 2008). Pathways of contaminants in the ecosystem depend on the system-composition, and remediation efficiency is influenced by the dynamics of plant communities. Therefore, it is necessary to better understand the relationships between adaptive responses of each plant species and its distribution in treatment wetlands. Exploring interspecies competitions between planted and invasive species in wetland cells and their ecological properties of wetland plant species is essential for treatment wetland design, construction, and successful operation management.

The overall Se removal efficiency (Gao *et al.*, 2003) and the significance of Se volatilization (Lin and Terry, 2003) in the Corcoran treatment wetlands have been previously presented. Based on weekly-monitoring results during a four-year study period, Gao *et al.* (2003) indicated that Se mass removal by the vegetated wetland cells was up to 78% of the Se mass input in 2000 (*i.e.*, during the fourth year). While treatment wetlands were utilized for the remediation of Se-contaminated drainage water, it was important to precisely determine the fate or partitioning of Se retained in the wetland cell. Therefore, a special effort was made to perform a complete and final characterization of seven treatment wetland cells in September 2000, four years after the wetland's inception. The objective of this paper was to determine the partitioning of Se mass retained in different compartments (including sediments, living plant material and litter, and standing water) of four-year-old-wetland cells at the time of sampling. The focus of this study was to explore the effects of invasive species on wetland plant management and the role of vegetation in Se partitioning in the treatment wetlands, which provides better understanding of the importance of wetland vegetation in the wetland design, construction and long-term management.

MATERIALS AND METHODS

Constructed Wetlands

Ten unlined wetland cells were built in May 1996, in Corcoran, central California, each measuring 15-m wide and 77-m long (approximately 0.29 acres per wetland cell) (Lin and Terry, 2003). Wetland soils were classified as Westcamp loam (a fine-silty, mixed,

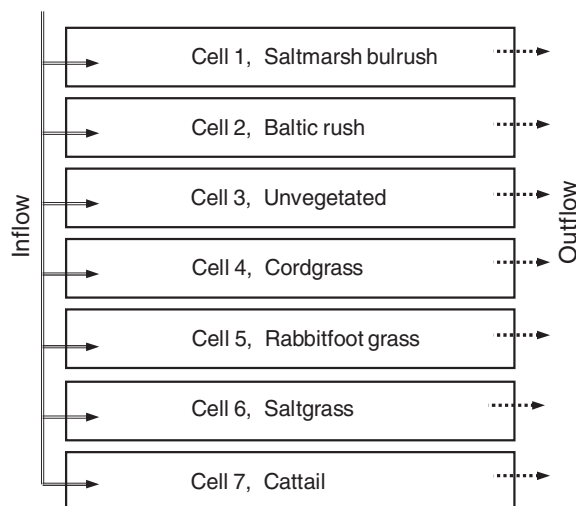


Figure 1 A field layout of the wetland cells vegetated with different plant species in Corcoran, California.

superactive, calcareous, and thermic Fluvaqueptic Endoaquept). Each wetland cell was tilled and fertilized with 16-16-16 type granular fertilizers at a rate of 45 kg (100 lb) per acre. After flooding with clean water to a water depth of 30 cm, four wetland cells were planted with transplants of baltic rush (*Juncus balticus* Willd) (Cell 2), cordgrass (*Spartina alternifolia* Loisel) (Cell 4), saltgrass [*Distichlis spicata* (L.) Greene] (Cell 6), and cattail (*Typha latifolia* L.) (Cells 7) at spacings of 50 to 100 cm, depending on the plant type. Saltmarsh bulrush (*Scirpus robustus* Pursh) (Cell 1) and rabbitfoot grass (*Polypogon monspeliensis* (L.) Desf.) (Cell 5) were planted from seeds in water saturated soils; and Cell 3 remained unplanted as a control. The field layout of these seven wetland cells is illustrated in Figure 1. Due to the similarity in wetland structure, monotypic vegetation, and field management, this study focused on Cells 1–7 to demonstrate differences between the plant species.

About 10 months after the wetlands were initially vegetated (May 1997), tile-drainage water was continuously supplied from a central collection basin to all wetland cells during a 4-year study period. Selenium concentrations in drainage water varied from 12 to 20 $\mu\text{g L}^{-1}$, and over 95% of the Se in drainage water was in the form of selenate (Gao *et al.*, 2000). The drainage water salinity ranged from 7 to 14 dS m^{-1} . Detailed hydraulic description and the weekly-monitoring results were previously given by Gao *et al.* (2003). In brief, the wetland cells had an in-cell water depth of 8–15 cm and a water retention time of 3–15 days during the study period of 1997–2000. Invasive plant species in wetland cells were under control during the first three years, but not in 2000.

Water, Plant, and Sediment Sampling and Total Se Analysis

The determination of species composition, coverage, and biomass production in each wetland cell and the collection of water, sediment and plant samples were carried out in September 2000, four years after the wetland's inception. Biomasses of plants were measured through five sampling areas (0.5 m^2) in each vegetated wetland cell. The plant coverage was determined for each plant species (planted or invasive) in each wetland cell

by 2 × 2-m grid mapping. The belowground root biomass was estimated by the ratio of shoot biomass to root biomass of the plant species. All aboveground shoots, standing litter and fallen litter were collected in each of the sampling areas, and at least five replicates of each type of samples (*i.e.*, living shoots, living roots, standing litter, and fallen litter) from each cell were used for total Se analysis. Sediments attached to plant root surfaces (within a few mm distance) were also collected separately to determine Se accumulation in rhizosphere sediment. All samples were transported and stored at 4°C until analyzed for Se. Five sediment cores were collected from each wetland cell. To examine the potential effects of vegetation on the retention of Se in sediments, additional sediment samples were also collected in central Cell 2 from the areas with baltic rush coverage and nearby areas (in > 1 m distance) without plant coverage. Sediments (0–25-cm depth) were taken with a sediment core sampler equipped with a replaceable butyrate liner (30 cm L × 5 cm D). The thin-walled probe was inserted into the sediment beyond the desired depth, then it was removed from the sediment, and the liner was removed from the probe and capped. The cores were brought back to the lab with dry ice and frozen at –20°C. The cores included plant material and overlying layers of detritus and organic material. At the room temperature, the cores were sectioned into the following layers: the detrital or sediment organic layer (0–3 cm); the mixed/transition layer (3–5 cm) for the top 5 cm; and every 5-cm down to a depth of 25 cm. Plant samples (shoot/root) were thoroughly rinsed in distilled water, oven-dried at 60°C, and ground in a Wiley Mill to pass through a 0.43-mm mesh screen. Sediment samples were air-dried and ground into fine powder. Ground plant and sediment samples were acid-digested with HNO₃/H₂O₂/HCl according to EPA method 3050B (USEPA, 1996), followed by Se concentration measurements according to Varian's procedure using an Atomic Absorption Spectrophotometer-Hydride Generator (VGA-77) (Lin and Terry, 2003).

Total Carbon in Sediments

Measurements of total carbon in sediments were conducted in Cell 2. Subsamples of air-dried sediments were ground to a very fine powder, and 50 mg of sediment was wrapped in a tin capsule and flash-combusted using a Carlo-Erba NC 2100 analyzer equipped with a mass spectrometer to determine total percent carbon content.

Statistical Analysis

Since it was difficult to establish true replicates for each treatment (*i.e.*, only one wetland cell for each plant species) due to the large scale of the wetland system, sampling was conducted using pseudoreplication (Hurlbert, 1984). In determining the difference between two wetland cells at the time of sampling, the null hypothesis tested was that there was no significant difference between the two cells (Lin and Terry, 2003). Statistical analysis was performed using the Statistical Analysis System (SAS), including the normality test of data and the *Tukey* multi-comparison of different means of Se concentration, and *Pearson* correlation (SAS Institute Inc., 1989).

RESULTS

Retention of Se in Sediment

The sediment Se concentrations decreased significantly with increasing sediment depth in the wetlands (Figure 2). Concentrations of Se in the top 3-cm depth of sediment

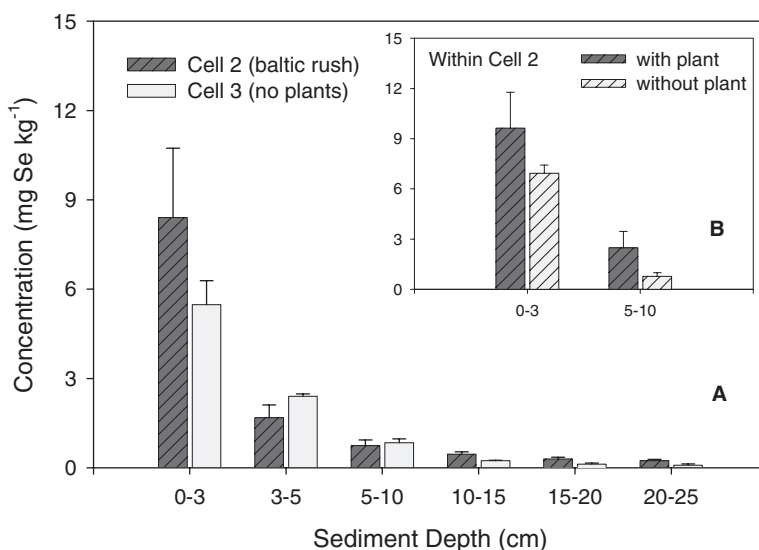


Figure 2 Effects of vegetation on Se accumulation at different depths of sediment. A: Se concentrations in sediment in Cell 2 (baltic rush) and Cell 3 (nonvegetated); B: Se concentrations in sediment from areas with plants versus no plants at the central section of Cell 2. Samples were collected in September 2000. Data shown are means and one standard error ($n = 6$ for Cell 2, $n = 3$ for Cell 3).

were significantly ($P < 0.05$) greater than the concentrations in the 3–5-cm depth of sediment. For instance, in the top 3-cm layer of sediment, Se concentration was 3–4 times higher than in the second layer (3–5 cm). Sediment Se concentrations below 10-cm depth remained near the background level ($< 0.5 \text{ mg kg}^{-1}$). In further comparing Se retention between vegetated and nonvegetated wetland cells, the total sediment Se concentrations in Cells 2 and 3 showed a similar distribution pattern of Se in sediment. However, the vegetated wetland cell tended to retain more Se in sediment than the nonvegetated wetland cell, although the difference is not statistically significant ($P > 0.05$) (Figure 2A).

Similar results were also observed in Cell 2 with baltic rush, the sediment from the vegetated areas also appeared to have higher levels of total Se concentration compared to the sediment from nonvegetated areas, but the difference is not statistically significant ($P > 0.05$) (Figure 2B). For the sediments that immediately surrounded the roots (*i.e.*, rhizosphere sediment), the Se concentrations were 2–4 times greater than the bulk sediment (*i.e.*, without roots) at a similar depth from nonvegetated regions in all vegetated wetland cells (Figure 3), suggesting that the presence of plant roots and rhizosphere microbes substantially increase Se retention in rhizosphere sediment.

Accumulation of Se in Plant Tissues

Because wetland invasive plant species were not under control during the last year of the study, the composition of plant species in some wetland cells has changed considerably from their original plantation by the time of sampling (fall 2000) (Table 1). Both Cells 5 and 6 were dominated with cattail after one year without invasive species control in the wetlands, while the rabbitfoot grass and saltgrass (originally planted) each covered only about 6% of Cell 5 and Cell 6, respectively. Cattail and saltmarsh bulrush species were the

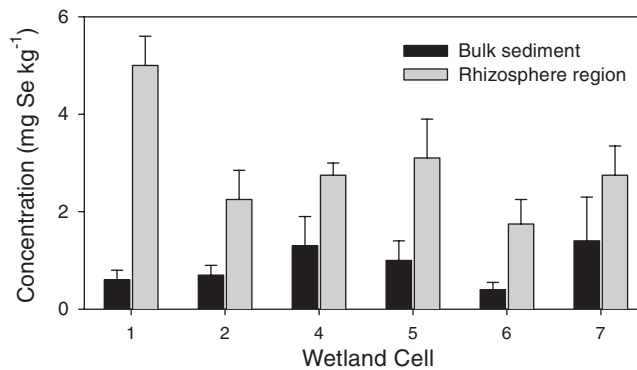


Figure 3 Selenium concentrations in the rhizosphere sediment (*i.e.*, sediments immediately surrounding the root surfaces, within a few mm) and the bulk sediment (5–10-cm layer, without roots) from areas without plants in September 1998. Data shown are means and standard deviation.

most competitive species in the wetland system, and rabbitfoot grass and saltgrass would eventually disappear due to invasion of cattail and saltmarsh bulrush after a long-term wetland operation. In Cell 2, the invasive species coverage of hardstem rush was 8.5%.

The biomass (g m^{-2} , DW) of each dominant species ($>8\%$ in coverage) in the wetland is shown in Figure 4A. Saltmarsh bulrush had the highest biomass production ($\text{g m}^{-2} \text{ y}^{-1}$) of living shoots in fall 2000. Cattail plants had the greatest biomass of standing litter. The biomass of fallen litter of each species was less than 300 g m^{-2} , and only accounted for small proportion of the total plant materials at the time of sampling. Overall, saltmarsh bulrush produced the greatest amount of plant materials (living shoot and root tissues and dead standing and fallen litter) (approximately 4 kg m^{-2}), followed by cattail (approximately 3 kg m^{-2}), baltic rush, and cordgrass. A relatively low biomass of cattail or cordgrass resulted from the lower density of each species at the time of sampling.

Concentrations of Se in different plant materials of each species are shown in Figure 4B. The Se concentration in living shoots or standing litter was generally $<5 \text{ mg kg}^{-1}$. The fallen litter of each plant species in different wetland cells accumulated

Table 1 Plant coverage of each species in the four-year old wetland cells after one year without invasive species control

Cell	Saltmarsh bulrush	Baltic rush	Cordgrass	Rabbitfoot grass	Saltgrass	Cattail	Hardstem rush	Cedar	Open water
1	97.2								2.8
2	2.4	83.2				0.2	8.5		5.7
3									100
4			78.9		6.4	1.2			13.5
5	14.4			6.8		78.4			0.5
6	7.3			1.2	6.8	80.3		0.2	4.3
7						99.5			0.5

The surface area of each wetland cell was 1155 m^2 . Values in bold represent the species originally planted (or open water area, Cell 3) for each wetland cell. Cell 3 was nonvegetated as a control.

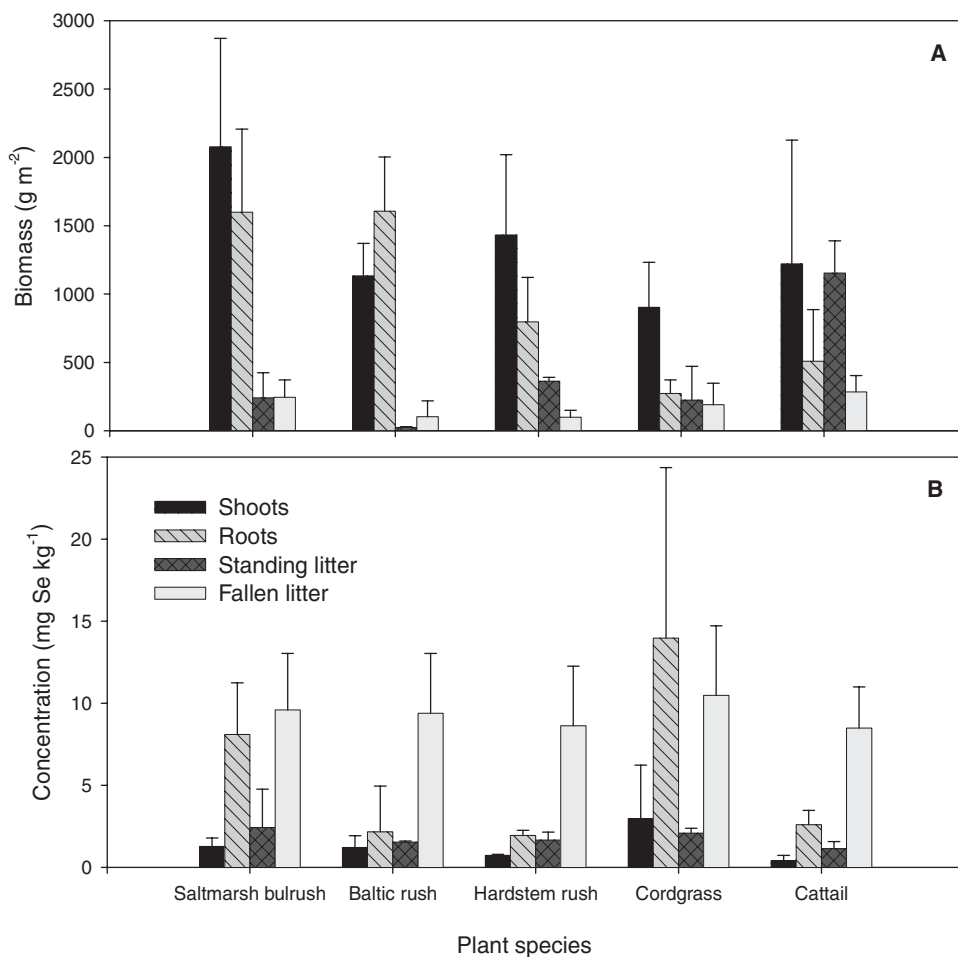


Figure 4 Biomass (DW) of plant shoot, root, standing litter, and fallen litter of five species in vegetated wetland cells (A) and Se concentrations in different plant materials of each species (B) in September 2000. Data shown are means and standard deviation ($n = 5$). No data were shown for rabbitfoot grass and saltgrass species because of their small coverage areas ($<10\%$) in the wetland cells due to other invasive plants.

comparable levels of Se (about 10 mg kg^{-1}). In general, concentrations of Se in roots tended to be higher than in the shoots for all species.

Partitioning of Se Mass Retained in Wetland Cells

The total Se mass distributed in the different vegetation components (*i.e.*, living shoot and root, standing litter and fallen litter) was determined for each vegetated wetland cell in fall 2000 (Figure 5). Results show that the living root tissues accumulated more Se than shoot tissues, and that saltmarsh bulrush roots contained the highest amount of Se mass, followed by cordgrass. The Se accumulation in standing litter ranged from 0.6 g per cell with saltmarsh bulrush to 1.5 g per cell with cattail. Cattail and saltmarsh bulrush had the largest amount of Se mass accumulated in fallen litter (2.7 g and 2.5 g Se per cell,

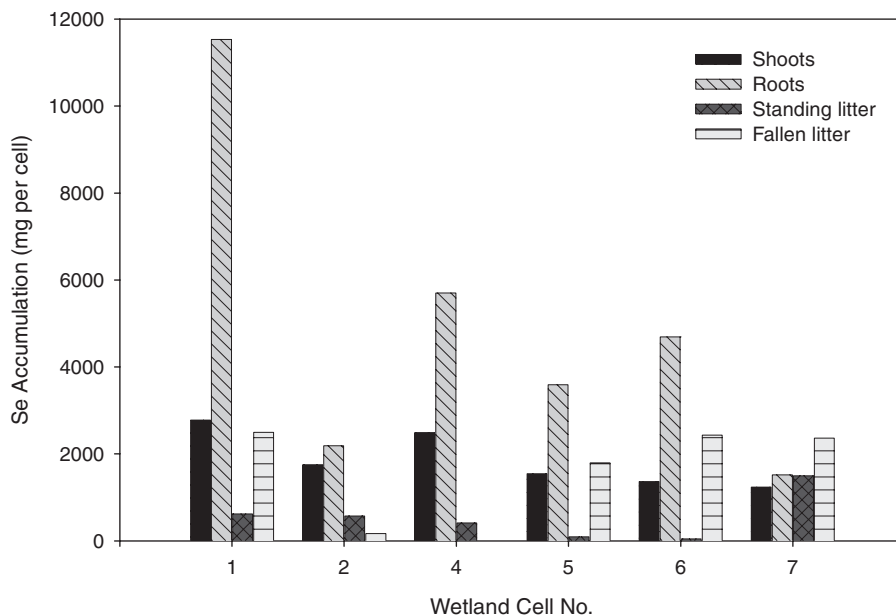


Figure 5 The total Se mass accumulated in plant materials, including living shoot and root, standing litter, and fallen litter, in each vegetated wetland cell in September 2000. The total Se mass included the accumulation of Se in the original planted species and all other invasive species.

respectively) at the time of sampling. Overall, Cell 1 retained the highest amount of Se in living and non-living plant tissues (Figure 5).

The total Se mass accumulated in plant materials in a wetland cell was relatively small, which accounted for less than 2% of the total Se mass that was retained in the wetland system (Table 2). In comparison, more than 90% of the total Se mass was retained in the top 10-cm layer of sediment, which includes rhizosphere sediments at the root-zone depth in vegetated wetland cells. In the sediment profile, the top 3-cm sediment was the major sink of Se retained in the wetland cell. Selenium remaining in standing water at the sampling time accounted for about 0.4% of the total Se mass, which was calculated from the Se concentration (approximately $10 \mu\text{g L}^{-1}$) and the volume of in-cell standing water (data not shown).

Total Carbon Distribution in Sediment

The total sediment carbon in Cell 2 was highest in the top 3-cm depth, and decreased with increasing sediment depth (Figure 6). No significant changes of total sediment carbon were observed within the depth of 5–20 cm. The distribution of total carbon significantly correlated with the distribution of Se in the sediment that was illustrated in Figure 2 ($r = 0.93$, $P < 0.0001$, $n = 10$).

Table 2 The partitioning of the total Se mass retained in different major compartments in the cordgrass wetland cell (Cell 4) and the unvegetated wetland cell (Cell 3)

	Cell 3 (unvegetated)	Cell 4 (cordgrass)
Total Se mass retained in wetland cell (g) [†]	348.6	474.7
Partitioning (% of the total Se mass)		
In-cell standing water	0.6	0.5
Sediments		
0–3-cm layer (with detritus)	59.7	47.9
3–5-cm layer	23.6	32.6
5–10-cm layer	16.1	16.8
Plant materials		
Shoots	— [‡]	0.5
Roots	—	1.2
Standing litter	—	0.1
Fallen litter	—	0.4

The partitioning of Se mass is presented as a percentage of the total Se mass retained in the wetland cell at the sampling time in September 2000. The comparison between the selected Cells 3 and 4 would enable us to identify the differences in Se mass partitioning between unvegetated and vegetated wetland cells. [†] = The total Se mass that was retained in the wetland cell at the time of sampling, which included the Se accumulated in sediment, plant materials, and standing water in the cell; and [‡] = not applicable.

DISCUSSION

Partitioning of Se Mass in Treatment Wetlands

Of the Se accumulated in the sediment and plant systems in the Corcoran wetland, about 48% of the Se was retained in the top 3-cm layer of the sediment, followed by about 33% and 17% in the 3–5 cm and the 5–10 cm layers, respectively, showing that the Se concentration decreased with increasing depth of sediment. This finding conforms to other observations in other wetland cells reported previously by Gao *et al.* (2003). Compared

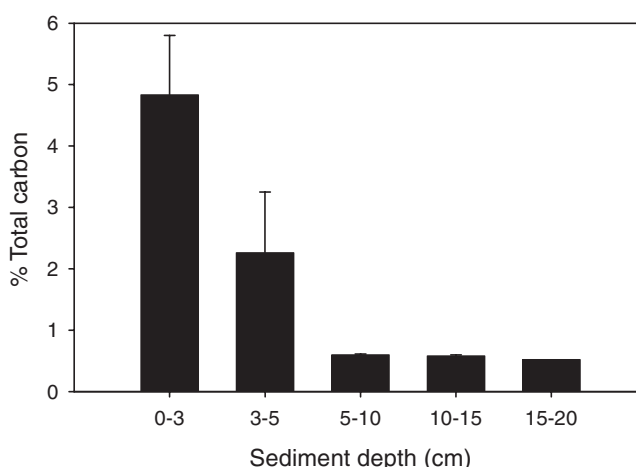


Figure 6 Changes in total carbon in sediments of Cell 2 (Baltic rush) with depth. Samples were collected in September 2000. The data shown are the mean and standard deviation ($n = 5$).

with this long-term field study at the Corcoran wetland, similar results have been obtained in other wetlands (Zhang and Moore, 1996; Hansen *et al.*, 1998), with respect to the extent of accumulation of Se in sediments and plant tissues. In this study, Cells 2 and 3 were selected because the comparison between the two cells would enable us to identify the differences in Se mass partitioning between vegetated and nonvegetated wetland cells.

Several mechanisms may account for the precipitation of Se from the water column to the surface sediment. These include various physio-chemical and biological processes (Bowie *et al.*, 1996): (1) the precipitation of Se-adsorbed particulates from water to sediment, (2) the reduction of soluble selenate to less soluble chemical forms, and (3) the decay of Se-laden biological materials and their accumulation on the surface sediment. Selenium (mainly selenite) can be sorbed onto suspended particulate matter (both mineral and organic) that flows into the wetland (Christensen, *et al.*, 1989). As the drainage water filters through the wetland, the particles settle on the sediment surface. Selenate can be reduced to selenite (SeO_3^{2-}) biologically and chemically under moderately reducing conditions (Tokunaga *et al.*, 1996). When selenate was reduced to elemental Se through both chemical and biological mechanisms (Frankenberger and Karlson, 1994; Myneni *et al.*, 1997), water insoluble elemental Se was precipitated into surface sediments. It has been proposed that the dissimilatory reduction of selenate to elemental Se carried out by microbes is the *major* process for the selenate removal from waters and the Se retention in the surface sediments (Weres *et al.*, 1989; Steinberg and Oremland, 1990; Zhang and Moore, 1997; Tokunaga *et al.*, 1998).

Role of Vegetation in Se Retention

Vegetation plays an important role in Se removal by treatment wetlands (Gao *et al.*, 2003). The nonvegetated, control wetland cell was the least efficient at removing Se from drainage water, compared to other vegetated cells. Among the plant species originally planted in the Corcoran wetland, the final in-cell coverage of cattail (Cell 7), saltmarsh bulrush (Cell 1), baltic rush (Cell 2), and cordgrass (Cell 4) were approximately 99, 97, 83, and 79%, respectively, over a 4-year time period. Rabbitfoot grass (Cell 5) and saltgrass (Cell 6) did not maintain their initial coverage; during the 4th year, these wetland cells were heavily invaded by cattail and saltmarsh bulrush. Earlier studies show no evidence that planting any particular species or combination of species resulted in a greater removal of Se from drainage water (Gao *et al.*, 2003). The accumulation of Se in plants accounted for only a minor proportion of the total Se mass removal by the wetland cells. Overall, about 2% of the total Se mass was partitioned in living (shoot and root) and dead plant materials (standing and fallen litter). Selenium concentrations were higher in the fallen litter and living roots (about 10 mg kg^{-1}) compared to the concentrations in living shoots and standing litter ($< 5 \text{ mg kg}^{-1}$). Because of their high Se concentrations and large biomass, living roots accounted for the highest proportion of the Se mass accumulated by plant materials (Table 2).

In comparing these Se concentrations with ones given in our previous reports (Terry, 1998; Lin and Terry, 2000), we found that no significant increase of Se concentration in plant shoots or roots in the wetland cells from year to year, except in Cell 4 where Se concentrations in living cordgrass shoot tissues were highest in fall 2000, changing from $0.9 \pm 0.2 \text{ mg kg}^{-1}$ in 1997 to $2.9 \pm 0.3 \text{ mg kg}^{-1}$ in Fall 2000. The present study with Se, as well as earlier studies with other trace elements, indicates that the major role of plants, including algae, in treatment wetlands is not to accumulate trace elements in plant tissues

(Horne, 2000; Ye *et al.*, 2001; Lesley *et al.*, 2008). The most important role of plant life is to provide carbon (fixed from photosynthesis), through death and decay, for the growth of microbes. Sediment microbes carry out important chemical conversions of trace elements to non-mobile forms, which in the case of Se, involves the reduction of selenate to elemental and organic Se (Lin and Terry, 2000). In addition, plants also provide organic carbon to microbes in root zone sediments through the secretion of root exudates and from the death and decay of fine roots. The increased population of microbes in the root zone, which is supported by organic carbon, facilitates the buildup of Se (mainly organoselenium) in the rhizosphere sediments. Clearly, this speculation was supported by the results obtained from the present study.

The decomposition of algae, bacteria, or plant materials containing high levels of Se on the surface of sediment will also contribute to the large proportion of Se mass retained in the surface sediment. The fallen litter acted as an important sink for Se adsorption or deposition in the wetland, regardless of vegetation species. Gustasson and Johnson (1992) reported that higher Se retention in the top sediment layer was associated with higher organic matter in the sediment. A correlation between the Se distribution and the sediment organic matter content was also observed at Kesterson Reservoir by Tokunaga and colleagues (1991). The organic matter in the surface sediments results from the decay of many different types of organism including plants, algae, bacteria, and invertebrates. In the present study, the total carbon content percent (%) was highest in the top 3-cm layer of sediment (Figure 6). A statistically significant correlation between the total Se concentration and the total carbon content in the sediment profile supports those previous findings that organic matter is a significant factor affecting Se accumulation and distribution in the wetland sediment. Indeed, future studies need to be carried out to explore potential impacts of seasonal vegetation changes on the transport and fate of Se in treatment wetlands.

Potential Ecotoxicity of Se Accumulated in the Wetland System

The ecotoxicity of Se is determined by the bioaccumulation of Se and its biotransformation as it passes through the food chain (Skorupa and Ohlendorf, 1991; Fan *et al.*, 1998). At prevailing environmental concentrations, dissolved selenate and selenite are only moderately toxic to aquatic organisms (Lemly, 1985). Organoselenium forms on the other hand, particularly selenomethionine (SeMet), are much more toxic to wildlife, despite their lower concentrations in water and soil (Hoffman and Heinz, 1988; USEPA, 1998). While plants and microorganisms may take up Se directly from the soil or water, most organisms at higher trophic levels, such as birds, obtain most of their Se from organisms containing protein-bound Se.

Fairly high concentrations of Se (*i.e.*, $>10 \text{ mg kg}^{-1}$) were found in the Corcoran treatment wetlands, such as 10 mg kg^{-1} in rabbitfoot grass roots, $10\text{--}17 \text{ mg kg}^{-1}$ in fallen litter, and $8\text{--}15 \text{ mg kg}^{-1}$ in the top 3-cm layer of sediment. An earlier study showed that most (up to 75%) of the accumulated Se in fallen litter was present as organic forms of Se, which, because of its greater ecotoxicity, might present a potential threat to wildlife (Lin and Terry, 2003). However, this threat could also be attenuated to some extent because organic Se compounds (like selenomethionine) can be volatilized at greater rates by both plants and microbes (Terry *et al.*, 2000; Lin *et al.*, 2002), and volatilization is beneficial because it removes Se from the local ground ecosystem to the atmosphere (Lin *et al.*, 2000).

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